

Time Machine at the LHC

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Abstract

Recently, black hole and brane production at CERN's Large Hadron Collider (LHC) has been widely discussed. We suggest that there is a possibility to test causality at the LHC. We argue that if the scale of quantum gravity is of the order of few TeVs, proton-proton collisions at the LHC could lead to the formation of time machines (spacetime regions with closed timelike curves) which violate causality. One model for the time machine is a traversable wormhole. We argue that the traversable wormhole production cross section at the LHC is of the same order as the cross section for the black hole production. Traversable wormholes assume violation of the null energy condition (NEC) and an exotic matter similar to the dark energy is required. Decay of the wormholes/time machines and signatures of time machine events at the LHC are discussed.

*"It's against reason," said Filby.
 "What reason?" said the Time Traveller.
 H.G. Wells, "The Time Machine"*

1 Introduction

Causality is one of fundamental physical principles. We suggest in this note that there is a possibility to test causality in experiments at CERN's Large Hadron Collider (LHC). This is related with a possibility of wormhole production in proton-proton collisions at the LHC. The wormholes contain small spacetime regions with closed timelike curves (CTC) which violate the standard causality condition.

A possibility of production in ultra-relativistic particle collisions of some objects related with a non-trivial space-time structure is one of long-standing theoretical questions. One of such particular objects is a black hole. Gravitational radiation in collision of two classical ultrarelativistic black holes was considered by D'Eath and Payne [1] and the mass of the assumed final black hole is estimated.

In general relativity there is Thorn's hoop conjecture which says that black holes form when, and only when, a mass M gets compacted into a region whose circumference in every direction is $\mathcal{C} < 4\pi GM$ [2]. The area of the corresponding disk is

$$\pi r_0^2 = 4\pi G^2 M^2 \sim s/M_{\text{Pl}}^4, \quad (1)$$

which gives a rough estimate for the classical geometrical cross-section for black hole production. Here G is the Newton constant, $M_{\text{Pl}} = 1/\sqrt{G}$ is the Planck mass and s is the square of the center of mass energy of colliding particles.

A conjecture that in string theory and in quantum gravity at energies much higher than the Planck mass black hole production emerges has been made in [3, 4]. It has been proposed to use the Aichelburg-Sexl shock wave metrics to describe ultra-relativistic particles. Under collision of these waves one can expect a production of black holes.

To speak on the production of black holes in quantum theory one should have a notion of a quantum black hole as a state (pure or mixed) in some Hilbert space. We have to compute the transition amplitude from a quantum state describing two particles to a quantum state describing quantum black holes. A quantum gravity approach to this problem is discussed in [5]. One considers the kernel of the transition amplitude

$$\langle h'', \phi'', \Sigma'' | h', \phi', \Sigma' \rangle = \int \exp\left\{\frac{i}{\hbar} S[g, \Phi]\right\} \mathcal{D}g \mathcal{D}\Phi \quad (2)$$

between configurations of the three-metric h'_{ij} and fields ϕ' on an initial spacelike surface Σ' and a configuration h''_{ij} and ϕ'' on a final surface Σ'' . In (2) the integral is over all four-geometries $g_{\mu\nu}$, including summation over different topologies, and field configurations Φ , which match given values on the space-like surfaces Σ' and Σ'' , i.e. $\Phi|_{\Sigma'} = \phi'$, $g|_{\Sigma'} = h'$ and $\Phi|_{\Sigma''} = \phi''$, $g|_{\Sigma''} = h''$. This formula assumes the Wheeler-de Witt formalism [20], for a recent review see [6].

To get the transition amplitude between two particles and a black hole, or a wormhole one has to integrate the kernel (2) with the wave function $\Psi_{\Sigma'}[h', \phi']$ describing two particles and the wave function $\Psi_{\Sigma''}[h'', \phi'']$ describing black hole or wormhole. An expression for the wave function of the ground state of a black hole is considered in [7].

In the case of a semiclassical description of black holes production from particles [5] a leading contribution comes from Σ' being a partial Cauchy surface with asymptotically simple past in a strongly asymptotically predictable space-time and Σ'' being a partial Cauchy surface containing black hole(s), i.e. $\Sigma'' - J^-(\mathcal{T}^+)$ is non empty where $J^-(\mathcal{T}^+)$ is the causal past of future null infinity, see [8].

A possible scenario for creation of black holes by using classical solutions of the Einstein equations has been proposed in [5]. In this scenario it is supposed that ultra-relativistic particles are represented by plane gravitational waves, which interacting collide and produce a black hole. A duality between plane gravitational waves and black holes is used. Trans-Planckian collisions in standard quantum gravity have inaccessible energy scale and cannot be realized in usual conditions. However if the fundamental Planck scale of quantum gravity is of the order of few TeVs [9] then one can argue that there is an exciting possibility of production of black holes, branes, and Kaluza-Klein modes from the extra dimensions in proton-proton collisions at CERN's Large Hadron Collider (LHC) [10, 11, 12, 13, 14]. The cross section for creation of a black hole or brane with radius r_0 was postulated to be approximately equal to the geometrical cross section πr_0^2 [12] as in the hoop conjecture (1). The Schwarzschild radius of a $4+n$ dimensional black hole of mass $M = \sqrt{s}$ is approximately,

$$r_0 \sim M_{4+n}^{-1} (s/M_{4+n}^2)^{\frac{1}{2(n+1)}}. \quad (3)$$

Here M_{4+n} is the $4+n$ dimensional Planck mass and the 4 dimensional Planck mass is given by

$$M_{\text{Pl}}^2 \sim V_n M_{4+n}^{2+n}, \quad (4)$$

where V_n is the volume of the extra dimensions.

This process can be achieved by scattering of two partons with the center of mass energy \sqrt{s} larger than M and impact parameter smaller than r_0 . For a discussion of different viewpoints see [15, 16].

D'Eath and Payne [1] have studied the problem of classical collision with zero impact parameter and shown that a closed trapped surface forms. This analysis was extended to a nonzero impact parameter by Eardley and Giddings [13]. The Aichelburg-Sexl solution has the form

$$ds^2 = -dudv + dx^{i2} + \varphi(x^i)\delta(u)du^2, \quad (5)$$

where φ depends only on the transverse coordinates x^i . A marginally trapped surface is constructed in the union of two incoming null hypersurfaces by solving a constraint problem for the Dirichlet Green's function.

In this note we consider a possibility of production of time machines at the LHC. In general relativity a timelike curve in space-time represents a possible path of an object or an observer. Normally such a curve will run from past to future, but in some space-times the curves can intersect themselves, giving a closed timelike curve (CTC) which is interpreted as a time machine. It suggests the possibility of time-travel with its well known paradoxes.

There are many solutions of the Einstein equations with CTCs. A list of such solutions includes Gödel's solution [17], van Stockum and Tipler cylinders [18], Kerr and Kerr-Newman solutions [8], Gott's time machine [19], Wheeler wormholes (space-time foam) [20], Morris-Thorne traversable wormholes [21], and Ori's dust asymptotically-flat space-time [22], see [23, 24] for a review. Chronology protection in AdS/CFT is considered in [25]. Gödel universes also appear in string theory and they are T-dual to pp -waves [26]. Euclidean wormholes are discussed in [28, 29]. Higher dimensional wormholes are considered in [30, 31].

A wormhole forms a handle-like geometry, whose two mouths join different regions of spacetime. If the wormhole is traversed from mouth to mouth, it acts as a time machine allowing one to travel into the past or into the future.

Violation of normal chronology is so objectionable an occurrence that any such solution could be rejected as unphysical. However, the Einstein equations are local equations and therefore one has to impose additional principles to preserve chronology. There are long debate concerning such principles [18, 23, 36, 37, 38, 40, 41]. In particular, in [36] it was shown that acausal CTC in Gott's universe cannot be realized by physical, timelike, sources.

An attempt to save causality and exclude CTCs from general relativity is Hawking's "chronology protection conjecture" which asserts that the law of physics do not allow the appearance of CTC [37]. However, there are not enough convincing arguments for this conjecture. Indeed, it was suggested that divergences in the energy-momentum tensor occur when one has closed causal curves. These divergences may create spacetime singularities which prevent one from traveling through to the region of closed timelike curves. However, it might be that quantum gravitational effects may smear out the divergences. Moreover, if one believes that there exists a full theory of quantum gravity, then chronology protection should be settled by using this theory [38].

Whether the chronology protection conjecture can be derived from the known physics laws or it is an independent postulate is still an open question. In this note we suggest to test it in experiments at the LHC.

Note that the CTC problem probably is related with the irreversibility problem well known in statistical physics. For a discussion of the black hole information paradox see [39] where it is explained that the black hole information paradox is a particular case of the irreversibility problem which is not solved not only for black *hole* but even for the usual black *body*.

2 Traversable Wormholes and NEC

The four-dimensional spacetime metric representing a spherically symmetric and static wormhole is given by [21, 23]

$$ds^2 = -e^{2\Phi(r)} dt^2 + \frac{dr^2}{1 - f(r)/r} + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (6)$$

Here $\Phi(r)$ is designated the redshift function and $f(r)$ is denominated the shape function. The radial coordinate r varies from $r = r_0$ corresponding to the wormhole throat, $f(r_0) = r_0$, to some R . The redshift function supposed to be finite, i.e. the event horizon is absent for

$r_o < r < R$ and the shape function should satisfy the following inequality $f'r - f < 0$. For asymptotically flat wormholes $R = \infty$. Wormholes with a cosmological constant are considered in [24].

As it is well known traversable wormholes exist only for NEC violating stress energy tensors [21]. According to the NEC [8] the stress energy tensor $T_{\mu\nu}$ has to satisfy the requirement $T_{\mu\nu}k^\mu k^\nu \geq 0$, where k^μ is a null vector, $k^\nu k_\nu = 0$. Using the Einstein field equations, $G_{\mu\nu} = M_{\text{Pl}}^{-1}T_{\mu\nu}$, one obtains [21] the following expression for the sum of the energy density $\rho(r)$ and the radial pressure $p_r(r)$

$$\rho(r) + p_r(r) = \frac{1}{M_{\text{Pl}}} \left(\frac{f'r - f}{r^3} + 2 \left(1 - \frac{f}{r} \right) \frac{\Phi'}{r} \right).$$

We see that the embedding condition together with the requirement of finiteness of the redshift function lead to the NEC violation on the wormhole throat.

Several scenario of the NEC violating have been considered in recent years. Generally speaking the NEC violating means instability. But this is true only under special assumptions. There are examples of stable effective theories where the NEC is violated [27]. In these particular cases the Lorentz invariance is broken and superluminal modes are present. Typical features of NEC violating effective theories is a presence of higher derivative terms and also superluminal modes. Gravitational Lorentz violation and superluminality take place also for wormhole solutions in Euclidean AdS gravity [29]. Note that traversable wormholes may be also supported by the dark energy (see for example [42, 43] and refs therein) with the equation of state parameter $w < -1$ [35].

In the brane world scenario, where the Universe is considered as a 3-brane embedded in a D-dimensional bulk, the four-dimensional Einstein field equations contain the effective four-dimensional stress energy tensor,

$$G_{\mu\nu} = M_{\text{Pl}}^{-1}T_{\mu\nu}^{\text{eff}}. \quad (7)$$

$T_{\mu\nu}^{\text{eff}}$ is a sum of the stress energy tensor of a matter confined on the brane, $T_{\mu\nu}$ and correction terms that arise from a projection of the D-dimensional Einstein equation to the four-dimensional space-time. It is possible that $T_{\mu\nu}^{\text{eff}}$ supported the four-dimensional wormhole solution violates the NEC meanwhile $T_{\mu\nu}$ does not violate the NEC.

In the simplest brane world scenario where the Universe is considered as a 3-brane embedded in a five-dimensional bulk these correction terms can be written explicitly [33, 34],

$$T_{\mu\nu}^{\text{eff}} = T_{\mu\nu} + \frac{6}{M_4\lambda}\Pi_{\mu\nu} - E_{\mu\nu}, \quad (8)$$

$$\Pi_{\mu\nu} = \frac{1}{12}T T_{\mu\nu} - \frac{1}{4}T_{\mu\alpha}T_{\nu}^{\alpha} + \frac{1}{8}g_{\mu\nu}[T_{\alpha\beta}T^{\alpha\beta} - \frac{1}{3}T^2], \quad (9)$$

$$E_{\mu\nu} = {}^{(5)}C_{\mu\alpha\nu\beta}n^{\alpha}n^{\beta}, \quad (10)$$

where ${}^{(5)}C_{\mu\alpha\nu\beta}$ is the five-dimensional Weyl tensor, $\alpha, \beta = 0, 1, 2, 3, 4$ and n^{α} is the unit normal to the brane. These formulas give the following relation between $\rho^{\text{eff}} + p_r^{\text{eff}}$ and $\rho + p_r$

$$\rho^{\text{eff}} + p_r^{\text{eff}} = \rho + p_r - \frac{1}{8\pi}(\epsilon + \sigma_r) + \frac{1}{\lambda}\rho(\rho + p_r). \quad (11)$$

Here $\rho(r)$ and $p_r(r)$ are the energy density and the radial pressure of the matter confined on the brane, ϵ and σ_r are diagonal components of the projected Weyl tensor $diag[\epsilon(r), \sigma_r(r), \sigma_t(r), \sigma_t(r)]$. Now to have a wormhole one has to provide the condition

$$8\pi(\rho + p_r)(1 + \frac{\rho}{T}) < \epsilon + \sigma_r. \quad (12)$$

As comparing with four-dimensional wormholes we see a softening of the energy condition. This relaxed condition appears due to corrections from the Weyl tensor in the bulk (compare with the NEC violation from the string field non-local action [42, 43]). For some particular examples it is possible to show that the four-dimensional effective stress energy tensor violates the NEC meanwhile the total five-dimensional stress energy tensor does respect the NEC [31]. We do not present here higher-dimensional solutions corresponding to wormholes on 3-brane. This is a subject of recent studies, see ref.[30, 31]. It would be interesting to find the wormhole solutions in the context of intersecting D5-branes related with the Standard model [44]. For a general class of solutions one expects the following dependence of the radius of the throat or mouth r_0 from the mass

$$r_0 = \gamma_{\text{wh}}(D) \frac{1}{M_D} \left(\frac{M_{\text{wh}}}{M_D} \right)^\alpha. \quad (13)$$

This formula is similar to the formula for the Schwarzschild radius for the D-dimensional Schwarzschild solution:

$$ds^2 = -(1 - (\frac{r_s}{r})^{D-3})dt^2 + (1 - (\frac{r_s}{r})^{D-3})^{-1}dr^2 + r^2 d\Omega_{D-2}^2, \quad (14)$$

where the Schwarzschild radius r_s is related to the mass of the black hole by the relation

$$r_s = \gamma_{\text{bh}}(D) \frac{1}{M_D} \left(\frac{M_{\text{bh}}}{M_D} \right)^{\alpha_{\text{bh}}}, \quad \alpha_{\text{bh}} = \frac{1}{D-3}, \quad (15)$$

where $\gamma_{\text{bh}}(D) = 1/\sqrt{\pi}(\frac{8\Gamma(D-1/2)}{D-2})^{1/(D-3)}$. Let us note that for solution (6) the radius of the throat r_0 is larger than the Schwarzschild radius: $r_0 > r_s$.

3 Wormhole Production at Accelerators

To compute the wormhole production cross section we can follow the approach for computation of the black hole production cross section [10, 11, 12, 13, 14]. The wormhole cross section is found from the partonic cross section for partons i and j to form a wormhole:

$$\sigma_{pp \rightarrow \text{wh}}(s) \sim \sum_{ij} \int_{\tau_m}^1 d\tau \int_{\tau}^1 \frac{dx}{x} f_i(x) f_j(\tau/x) \sigma_{ij \rightarrow \text{wh}}(\tau s). \quad (16)$$

Here \sqrt{s} is the center of mass energy, x and τ/x are the parton momentum fractions, and f_i are the parton distribution functions. The parameter $\tau_m = M_{\text{min}}^2/s$ where M_{min} corresponds to the minimum mass for a valid wormhole description. f_i are the Parton Distribution

Functions (PDFs), (we suppress here transfer momenta). This formula is the same as the formula for black hole production, the difference being only in numerical factors.

The geometrical cross section of the wormhole production is

$$\sigma_{ij \rightarrow \text{wh}}(s) = \pi F(\sqrt{s}/M_D) r_0^2(\sqrt{s}, M_D). \quad (17)$$

The form factor $F(\sqrt{s}/M_D)$ incorporates the theoretical uncertainties in description of the process, such as the amount of the initial center mass energy that goes into the wormhole, the distribution of wormhole masses as function of energy. These corrections are similar to corrections in the formula for black hole production.

4 Conclusions

Causality is the fundamental physical principle. In quantum field theory causality and the spacetime picture of the high energy scattering were considered in [45, 46, 47]. If there are spacetime regions with CTC (time machines) then causality is violated.

In this note we suggested to test causality by using experiments at the LHC. We argued that if one can trust the classical geometrical estimate of the cross-section for the black hole production, if there exists an exotic matter similar to the dark energy, and if the scale of quantum gravity is of the order of few TeVs then one can expect the production of time machines/wormholes in the proton-proton collisions at the LHC of the same order as the cross section for the black hole production. This would lead to violation of the standard causality condition. Further studies of the experimental signatures of the wormhole production are required since there are transitions between black holes and wormholes [48].

It would be interesting to explore in some details the formula (2) for the transition amplitude between colliding quantum particles and black holes/wormholes which should be integrated with the wave function of the wormholes.

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Note Added

After submission to the arXiv of the first version of this paper, there appeared a paper[49] discussing possible observable traces of mini-time-machines. It seems the important question on possible experimental signatures of time machines deserves further explorations.

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